

Detecting and characterising an englacial conduit network within a temperate Swiss glacier using active seismic and ground penetrating radar

Gregory Church^(1,3), Andreas Bauder⁽¹⁾, Satyan Singh⁽²⁾, Lasse Rabenstein⁽³⁾, Hansruedi Maurer⁽³⁾



Motivation

Englacial hydrology plays an **important role** in routing surface water to the glacier's bed and it consequently **affects** the **glacier's dynamics**.

Goal of research

Can we **detect** an **englacial conduit network** within an alpine glacier (Rhône Glacier, Switzerland).

Are we able to **resolve** and **characterize** the system using comprehensive **geophysical data (active seismic & radar)** and **borehole observations**.



Detecting and characterising an englacial conduit network within a temperate Swiss glacier using active seismic and ground penetrating radar (GPR)

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1. Introduction

2. Survey Site &
Data Acquisition

3. Results

4. Interpretation &
Conclusion

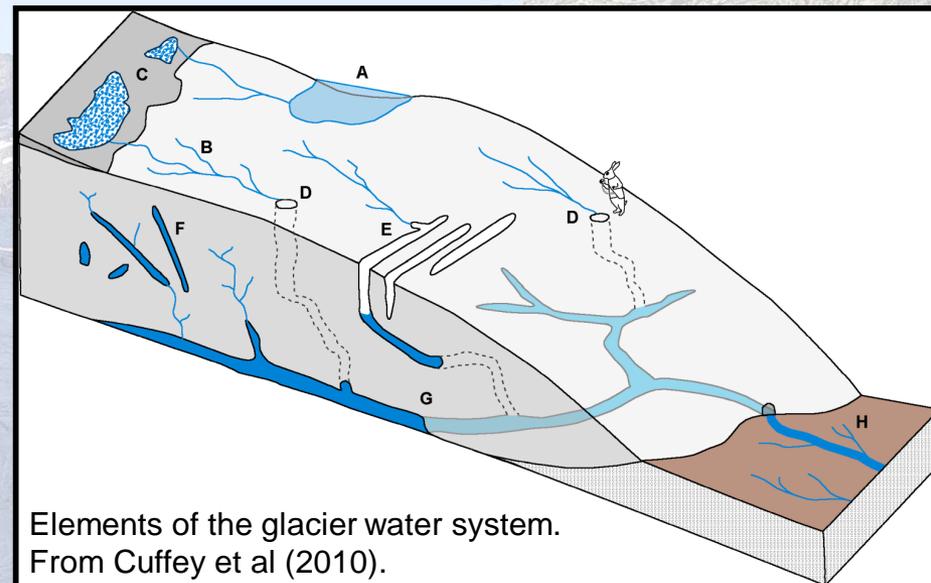


1. Introduction

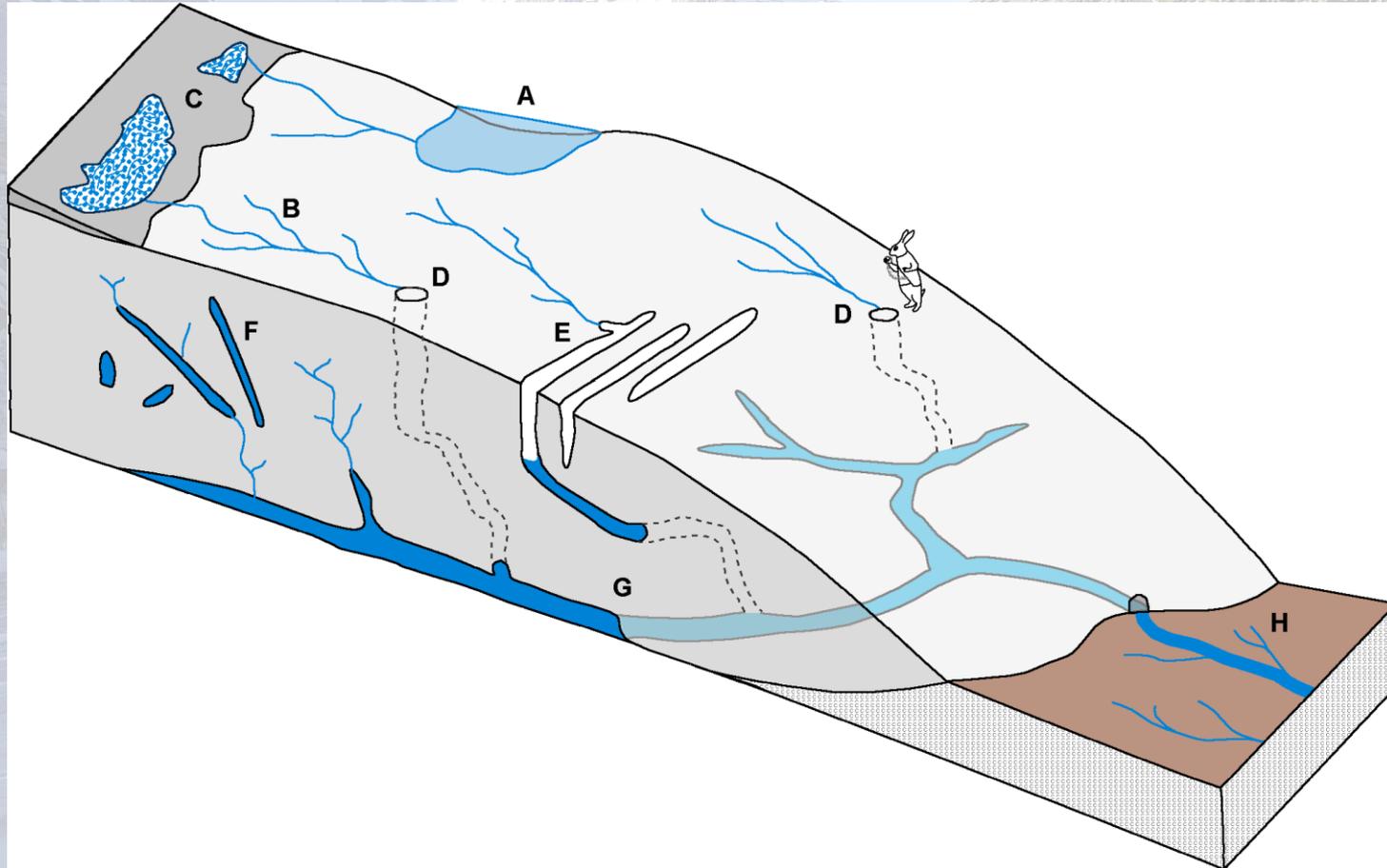
The aim of this study is to detect and characterise englacial conduits within a temperate glacier using geophysical analysis.

The study is motivated as englacial hydrology plays an important role in routing surface water to the glacier's bed. Therefore, englacial hydrology consequently affects the glacier's dynamics. However, it is often difficult to observe englacial conduit conditions on temperate glaciers because of their short-lived nature.

Geophysical methods can be used to image and characterize the glacier's hydrological system. Active seismic and ground penetrating radar (GPR) surveys offer complementary information on the the glacier's interior over large areas



1. Introduction



Elements of the glacier water system. Englacial conduits features are sourced by surface streams (B) entering englacially from either moulin (D) or crevasses (F). There also exist water filled fractures englacially (F) that can become hydraulically connected and convey water. (White rabbit is approximately 10 m tall for scale) From Cuffey et al (2010).

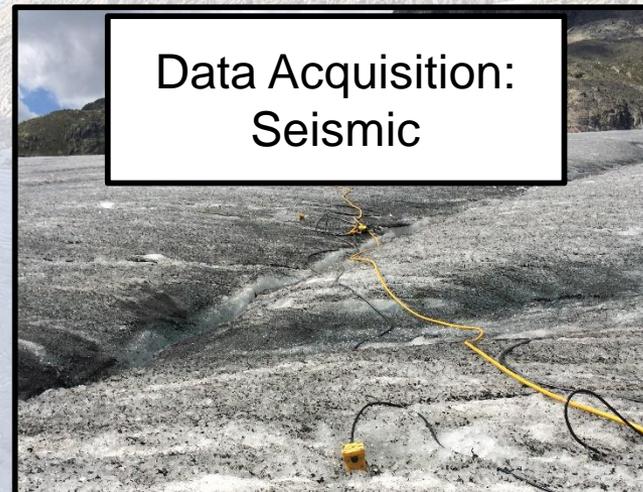


2. Survey Site & Data Acquisition

Survey Site Location



Data Acquisition: Seismic



Data Acquisition: GPR

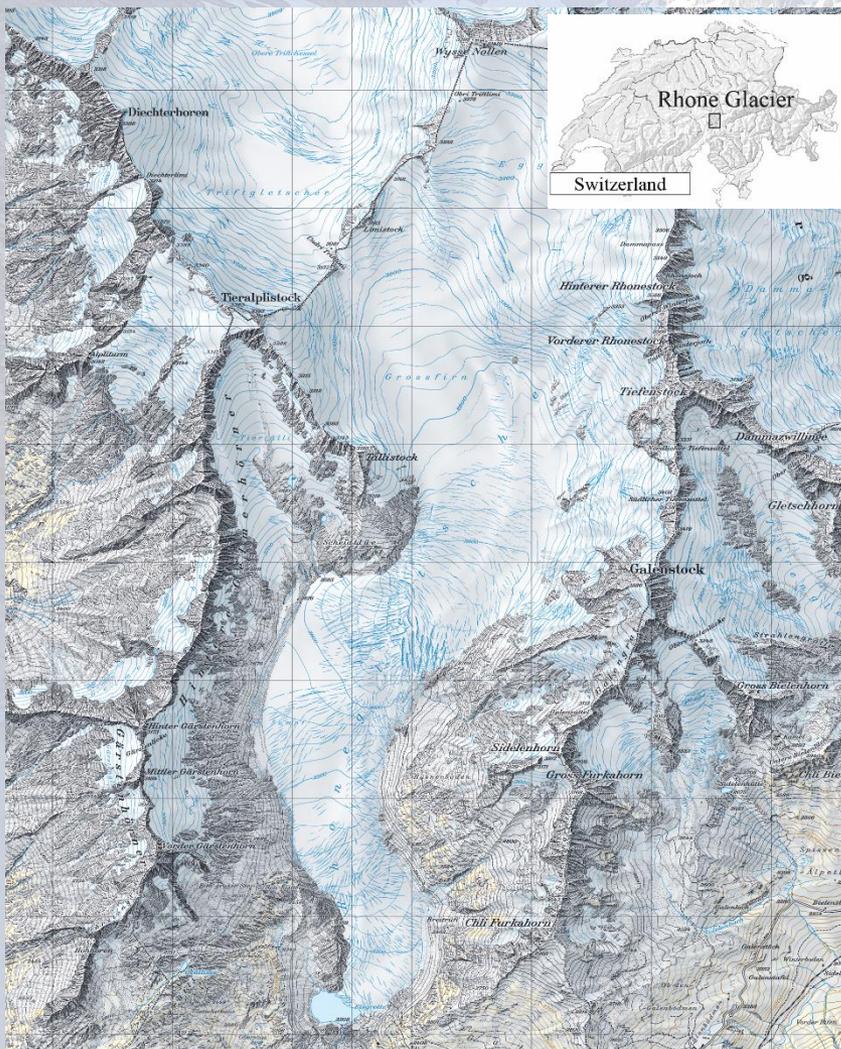


Data Acquisition: Borehole





2. Survey Site



- The Rhone Glacier is located in the central Swiss Alps.
- It is flowing southwards from 3556 m until 2208 m where it meets a proglacial lake.
- The proglacial lake formed in 2005 and is expanding. It remains at a constant 2208 m AMSL as a result of the granite riegel.
- Due to the increased glacial retreat, the proglacial lake is expanding (Church et al 2018) and therefore, the lake is a potential candidate for hydropower generation.

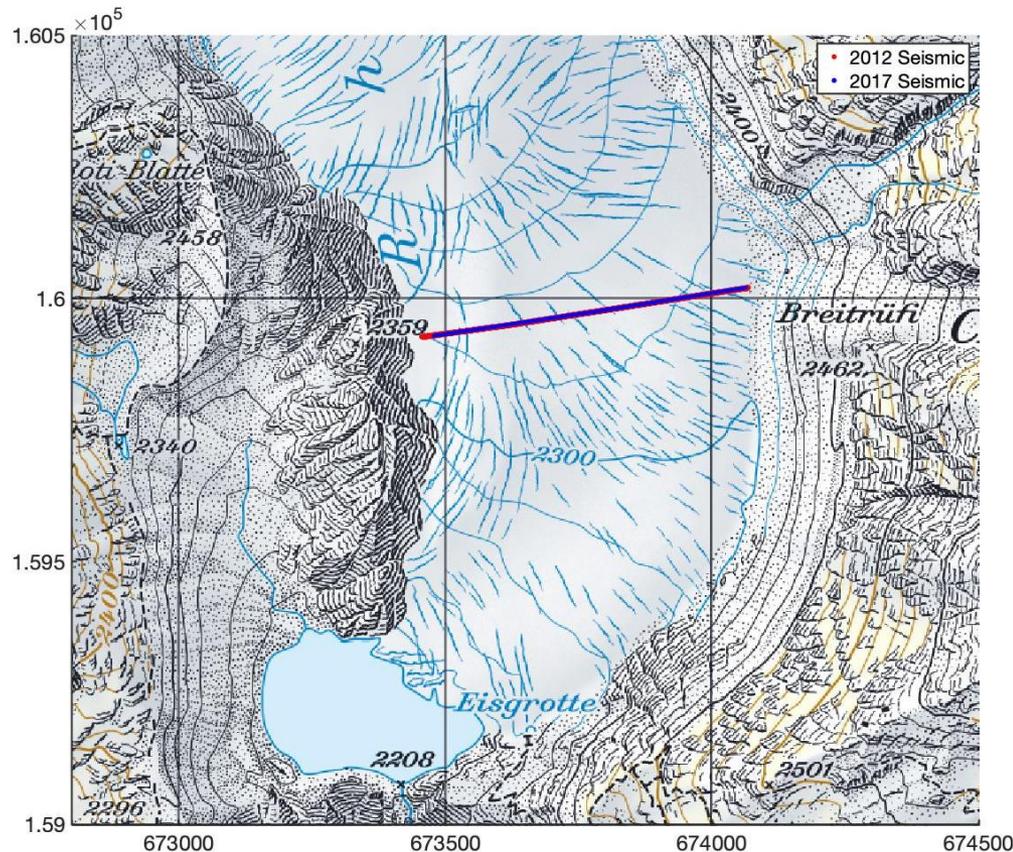
Survey Site Location

Data Acquisition:
SeismicData Acquisition:
GPRData Acquisition:
Borehole



2. Data Acquisition: Seismic (Slide 1/2)

- Active seismic acquired in September 2012 and August 2017 to image englacial structure and detect any significant changes between 5 years.





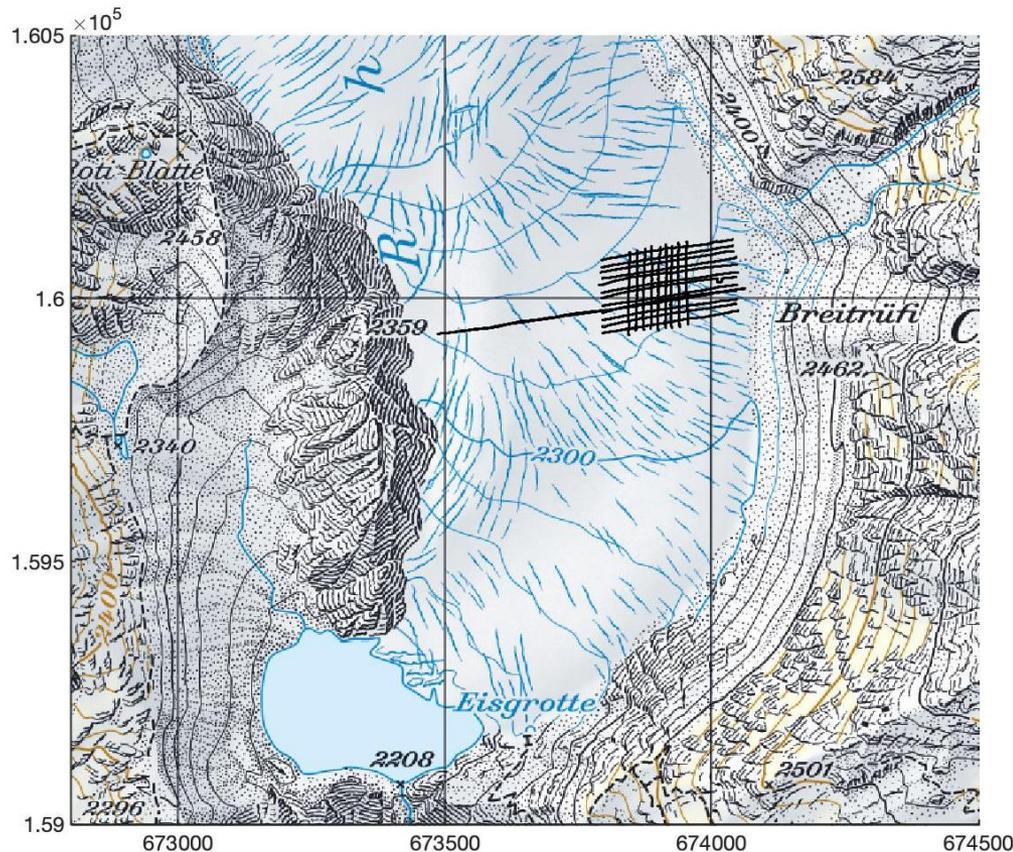
2. Data Acquisition: Seismic (Slide 2/2)

Seismic Acquisition Parameter	2012	2017
Profile Length	624 m	591 m
Shot Spacing	4 m from 0 to 192 m 8 m from 192 m to 624 m	8 m
Receiver Spacing	2 m	4 m
Geophones	30 Hz (Z-Component)	
Roll-Up Geometry	Yes	No
Source Type	75 g explosives (RIODIN HE)	
Common Mid Point Spacing	1 m	2 m
Fold of coverage	60 (with 4 m shot spacing) 30 (with 8 m shot spacing)	30



2. Data Acquisition: GPR

- Grid of GPR profiles over englacial features using PulseEKKO Pro System with 25 MHz antennas acquired in 2018:

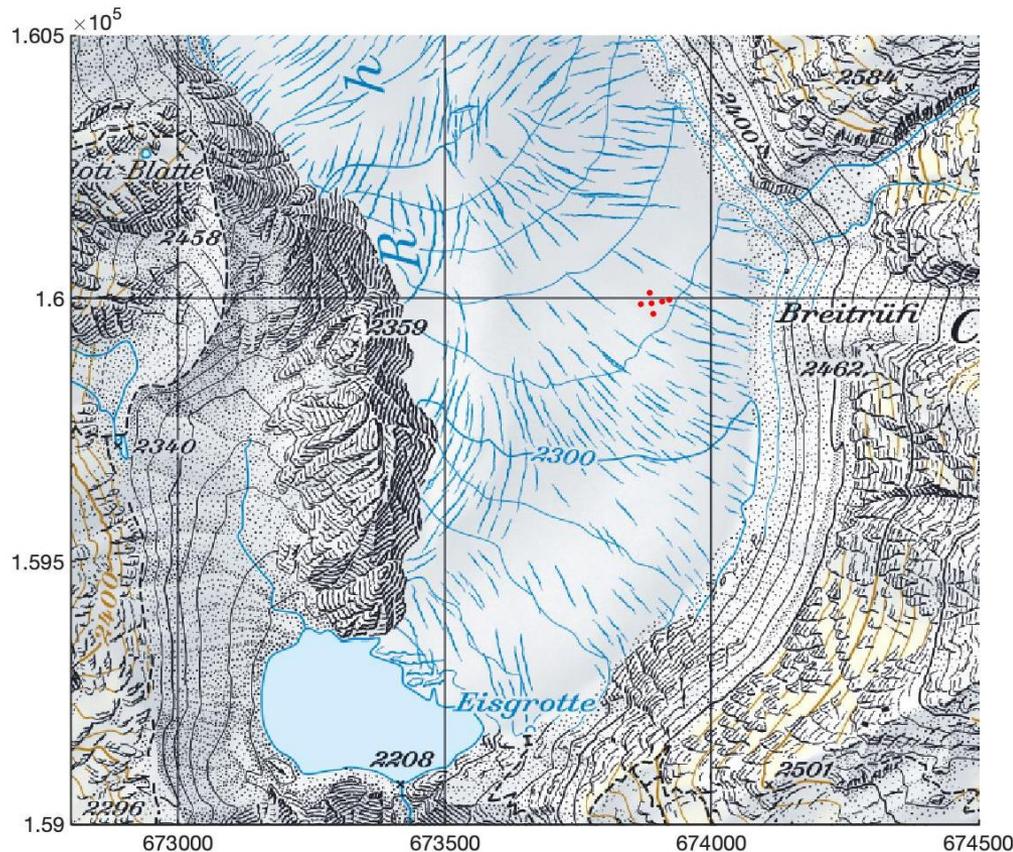


- Antennas were orientated parallel to the flow in order to generate stronger and more coherent bedrock and englacial reflections.



2. Data Acquisition: Borehole

- 6 boreholes were drilled into any potential englacial conduit networks using a hot water drilling system.

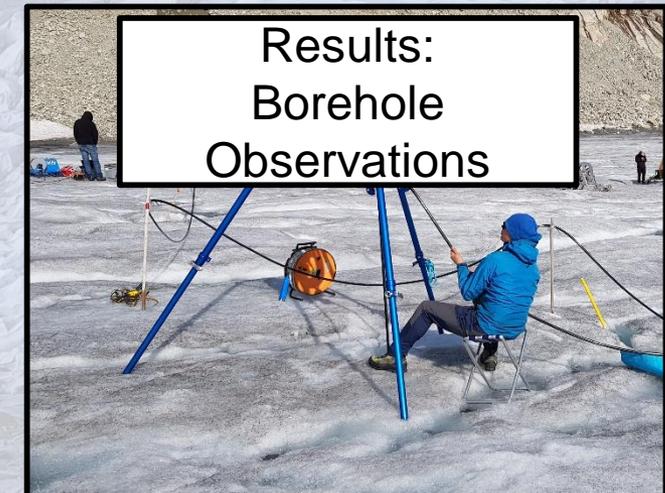
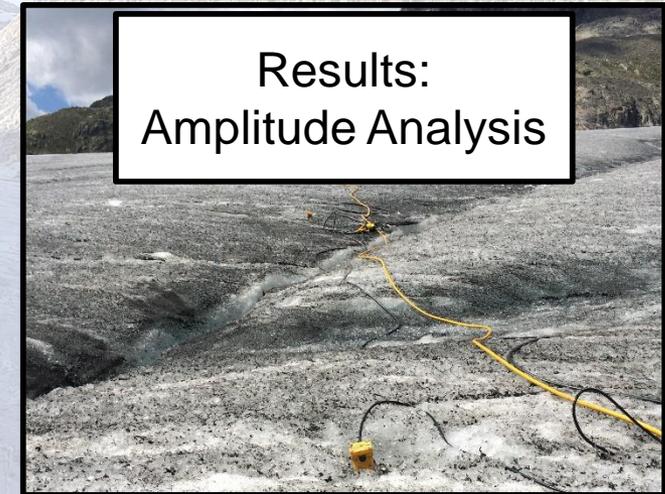
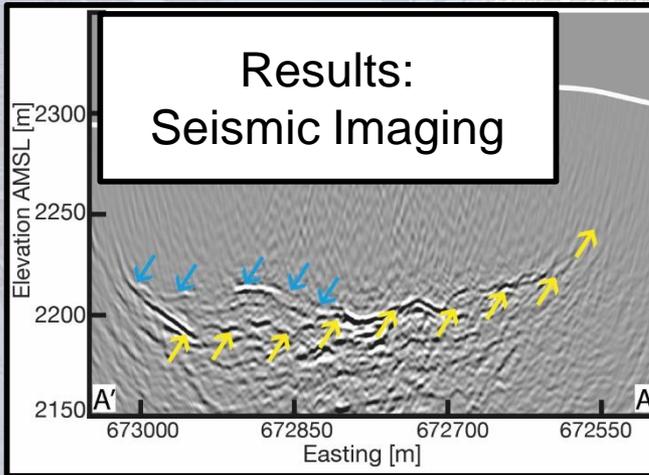


- A GeoVISIONTM Dual-Scan borehole camera from Allegheny Instruments was lowered into the feature to provide direct observations.





3. Results

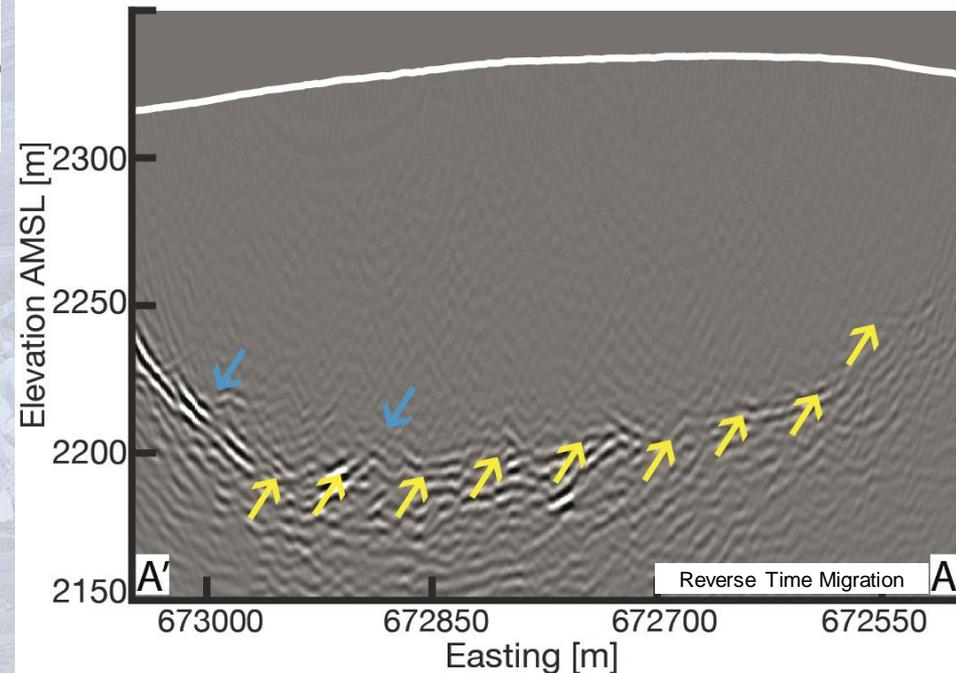
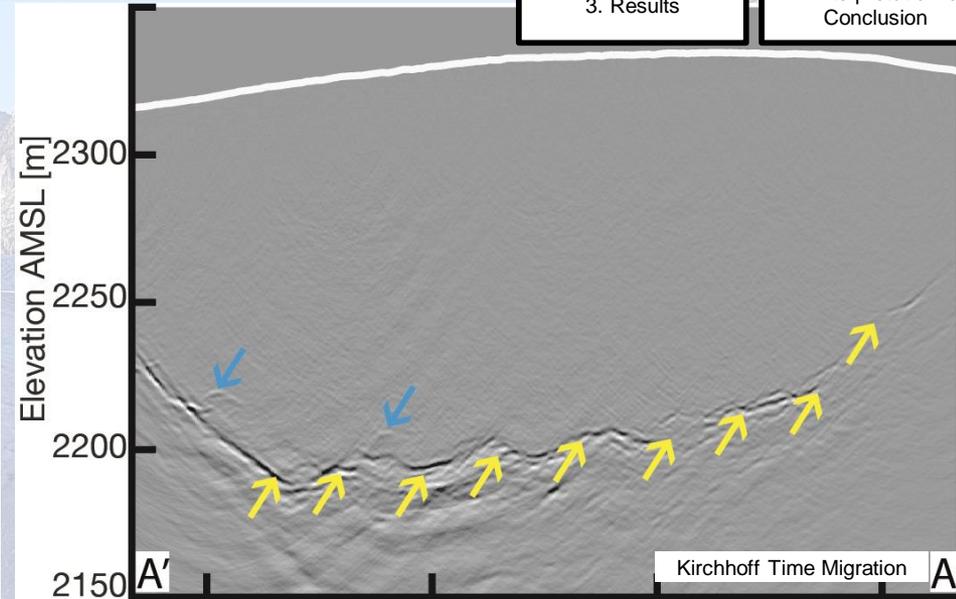
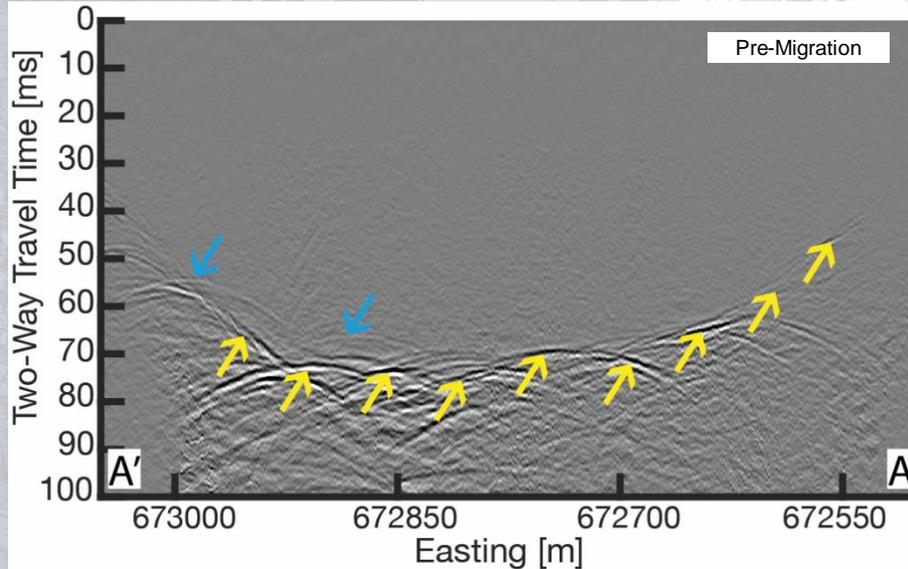




3. Results: 2012 Seismic Imaging

Click for 2017
results

Click for seismic
processing details



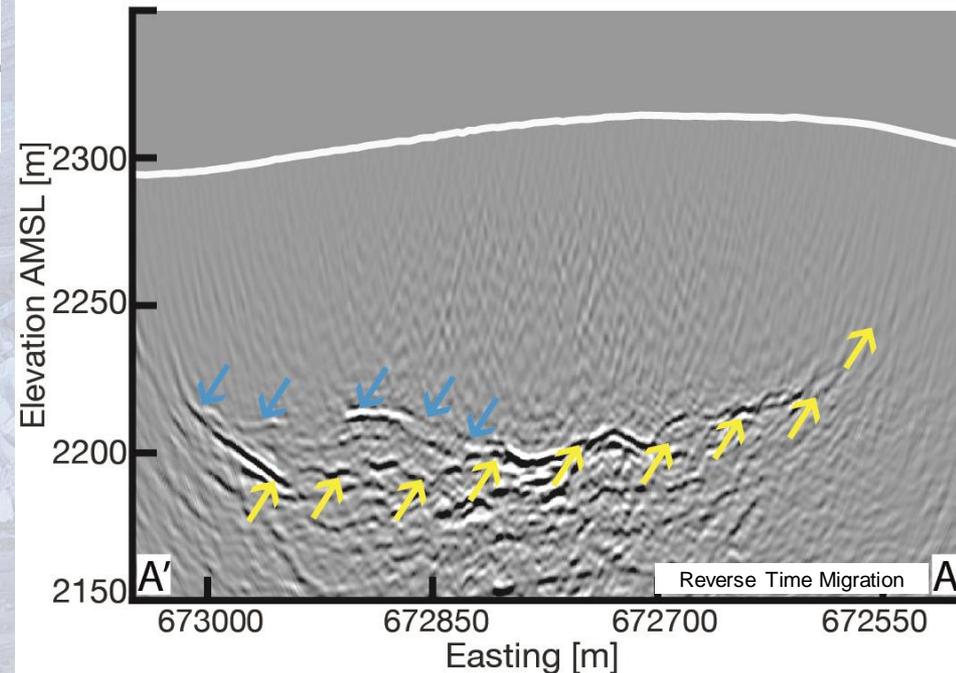
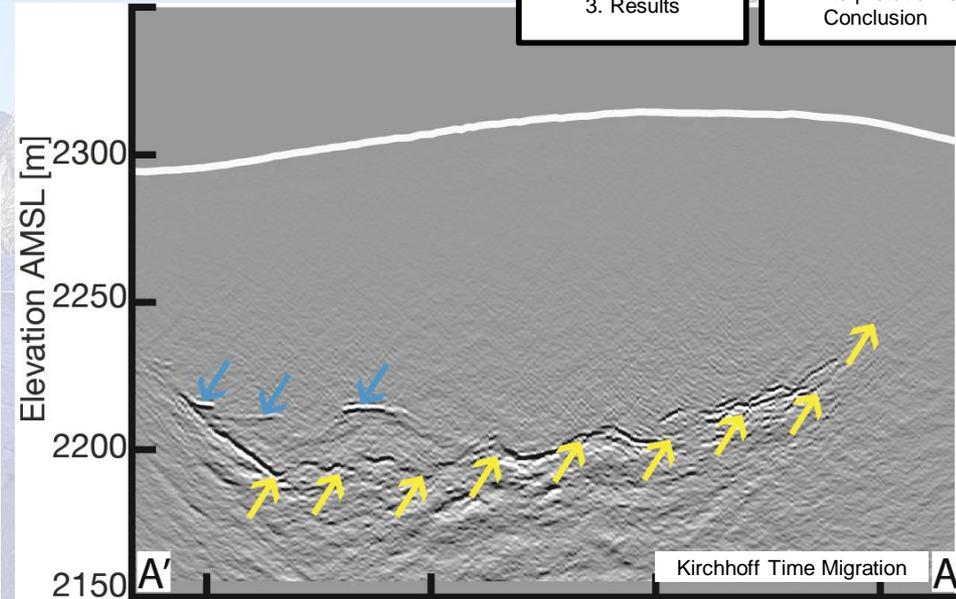
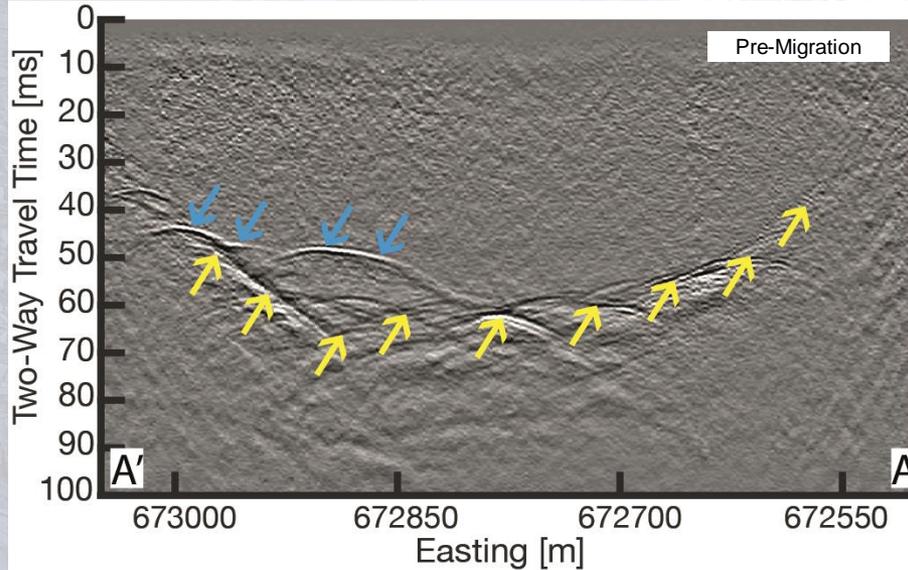
- Seismic imaging provided a cross-sectional view into the Rhone glacier.
- Highly resolved and strong bedrock reflection (yellow arrows).
- Weak englacial reflection (blue arrows).
- Two different imaging algorithms presented.
 - Kirchhoff = summation along diffraction curves.
 - Reverse Time Migration = two way solution to wave equation



3. Results: 2017 Seismic Imaging

[Click for 2012
results](#)

[Click for seismic
processing details](#)



- Well correlated bedrock reflection (yellow arrows) between 2012 and 2017 providing confidence in data quality.
- Strong englacial reflection (blue arrows) indicating development of englacial feature between 2012 and 2017.
- RTM provides improved englacial imaging and able to interpret englacial reflection and connect with basement.

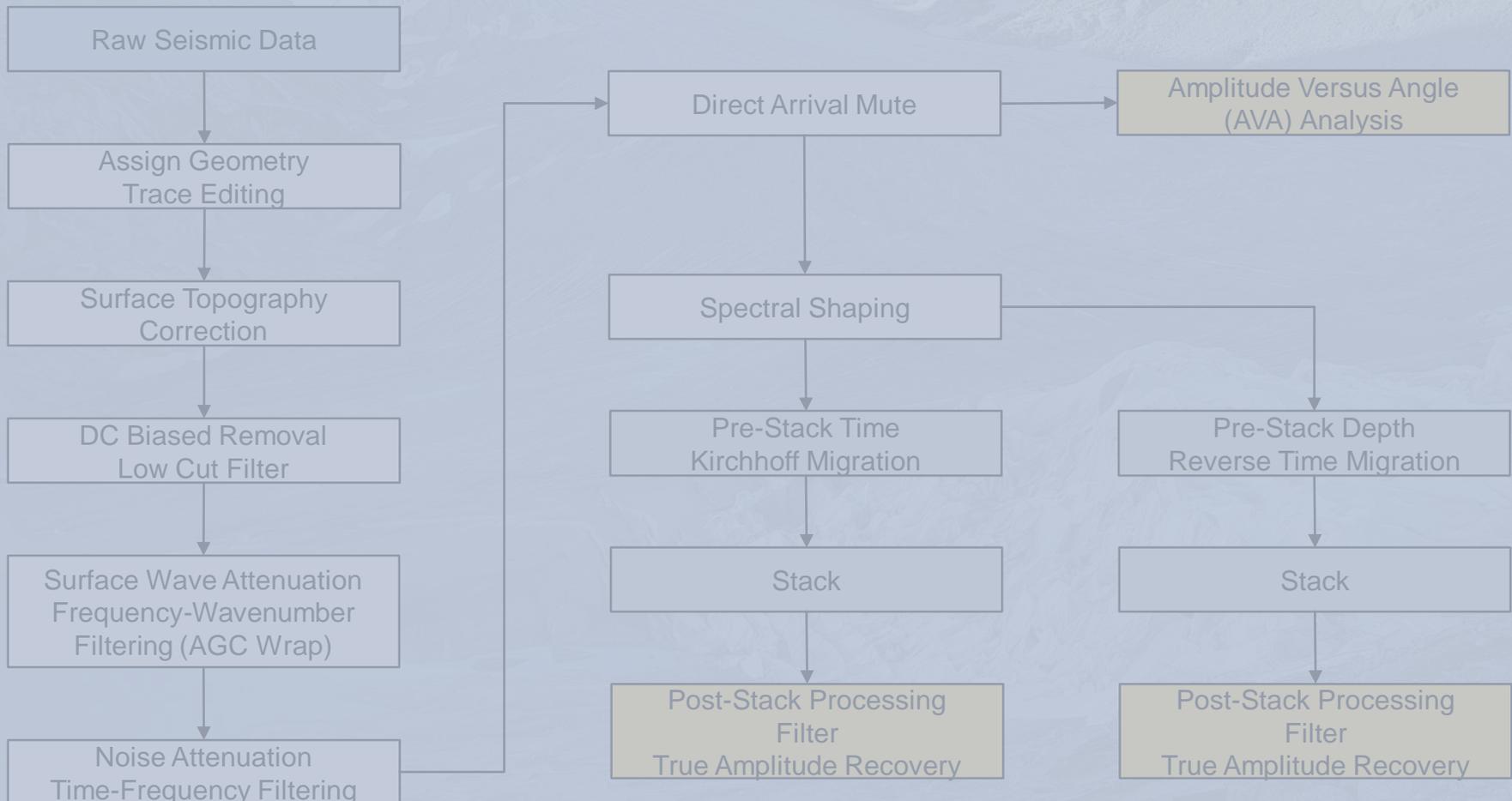


3. Results: Seismic Processing

There are 2 dataset outputs:

Imaging

Amplitude Analysis



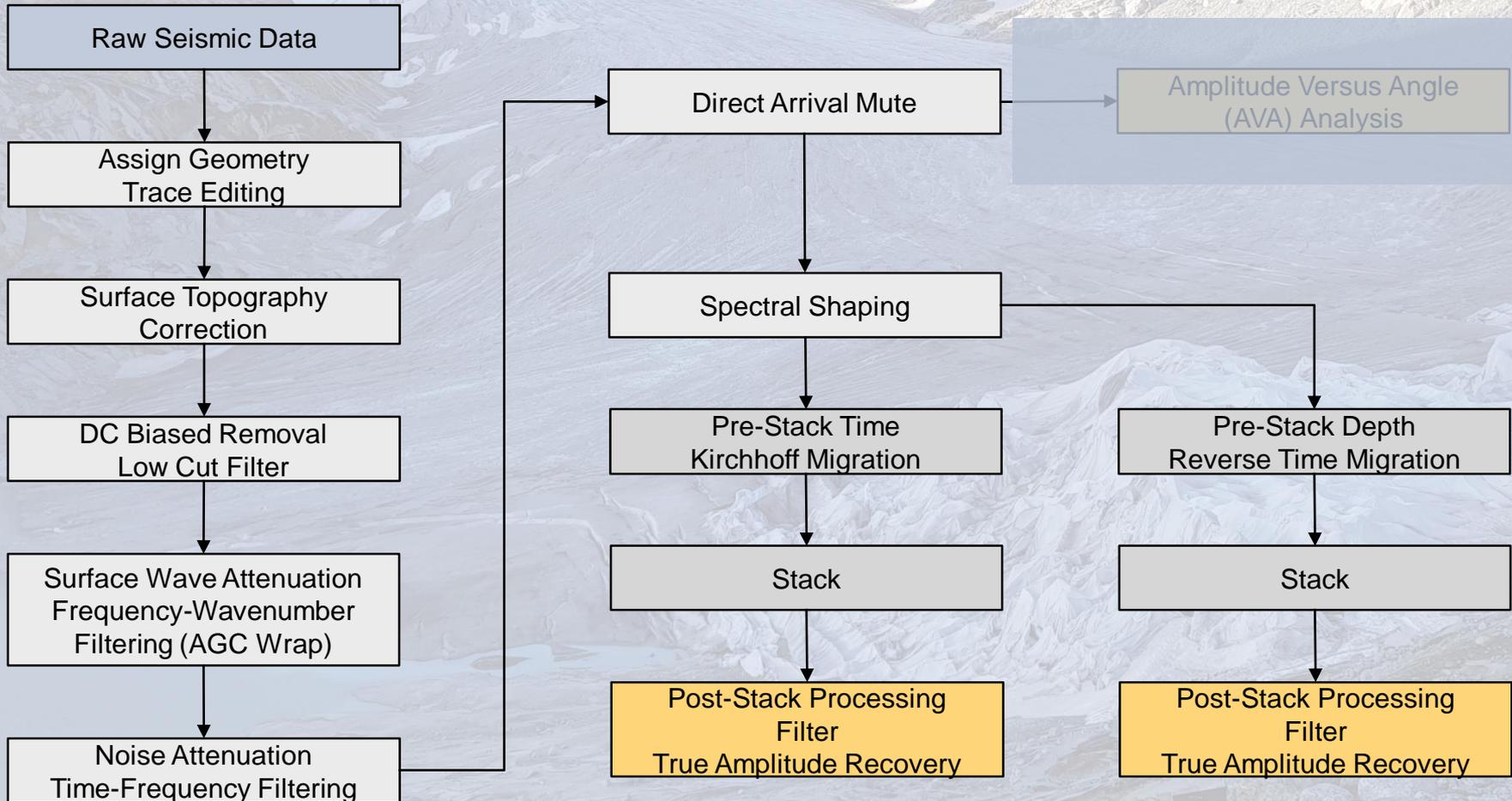


3. Results: Seismic Processing

There are 2 dataset outputs:

Imaging

Amplitude Analysis



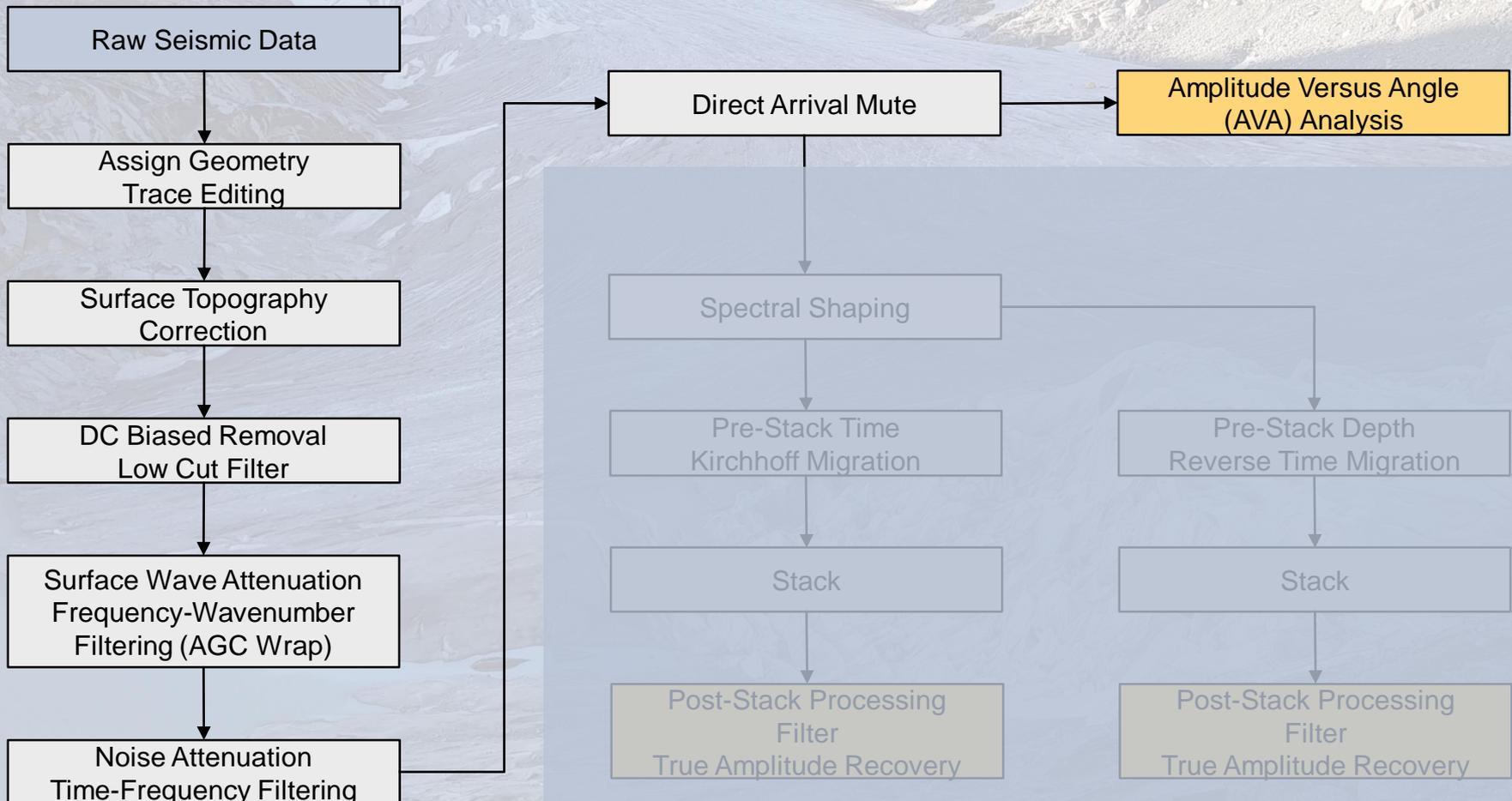


3. Results: Seismic Processing

There are 2 dataset outputs:

Imaging

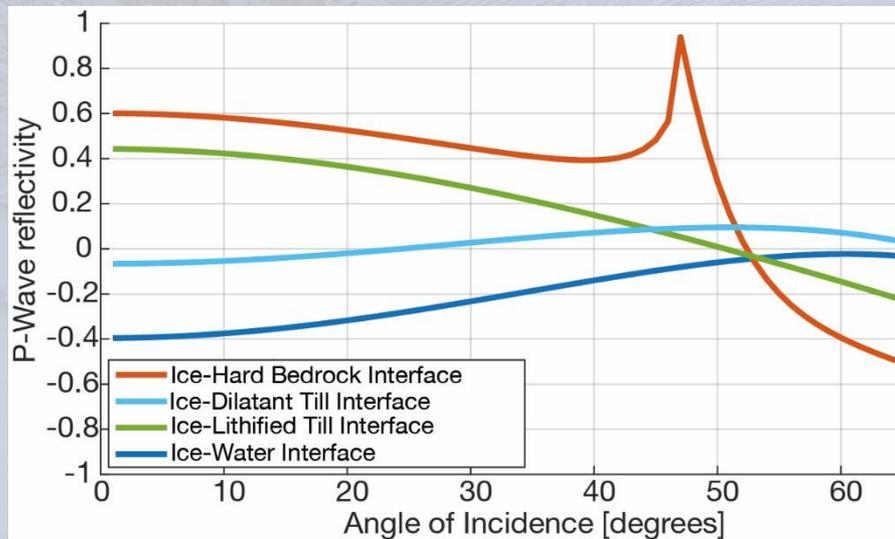
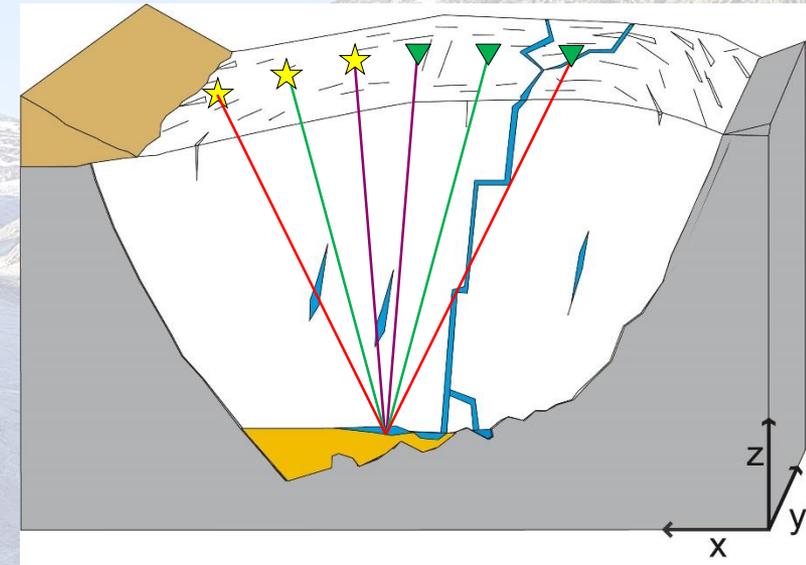
Amplitude Analysis





3. Results: Amplitude Analysis (Slide 1/2)

- Englacial material properties can be estimated by analyzing the amplitude from the reflected waves.
- The amplitude is a function of incidence angle and elastic properties (density and seismic wave velocities) (Aki et al 2002).
- The reflectivity can be calculated using the Zoeppritz equations (function of: V_p , V_s and ρ).



Common Midpoint Gather

Source-Receiver Offset





3. Results: Amplitude Analysis (Slide 2/2)

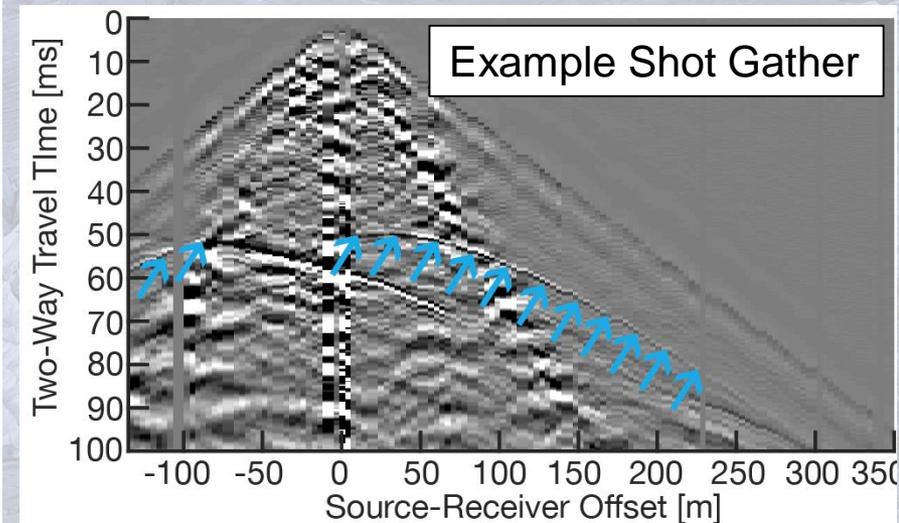
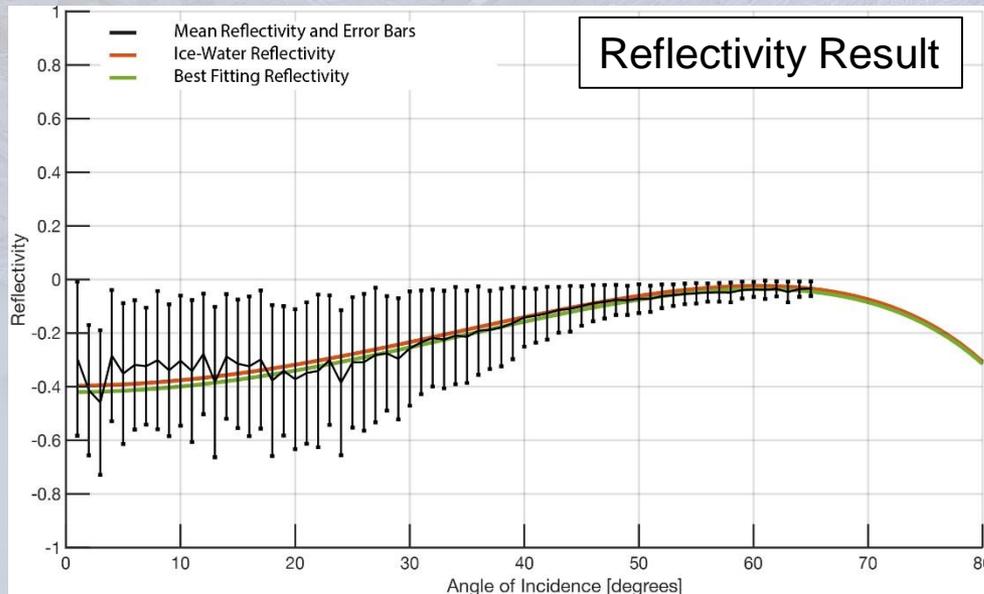
- Reflectivity was estimated using an inversion based methodology described by Dow et al. (2013).

- The reflectivity is found using:
$$R(\theta) = \frac{A_r(\theta)}{A_0 d_r(\theta) e^{(\alpha_p \cdot d(\theta))}}$$

$A_r(\theta)$ ← Amplitude of recorded reflection
 A_0 ← Source Amplitude (A_0), spherical divergence (path length, d), Anelastic attenuation (α_p)

- Where the attenuation α_p was estimated from cross-hole seismic experiments and the source amplitude A_0 was determined using estimated first order multiple amplitude A_m :

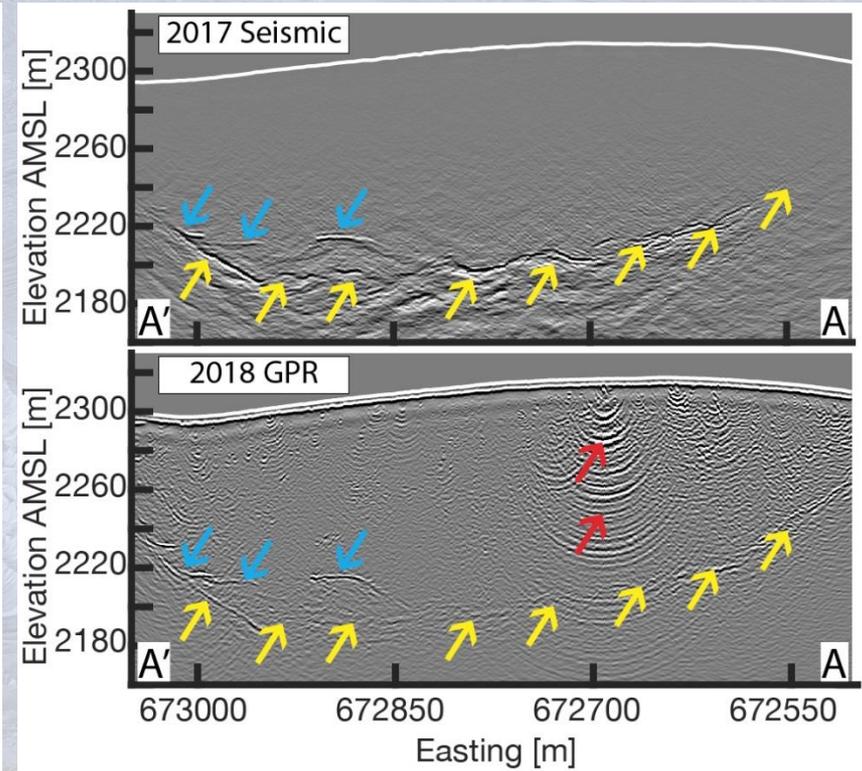
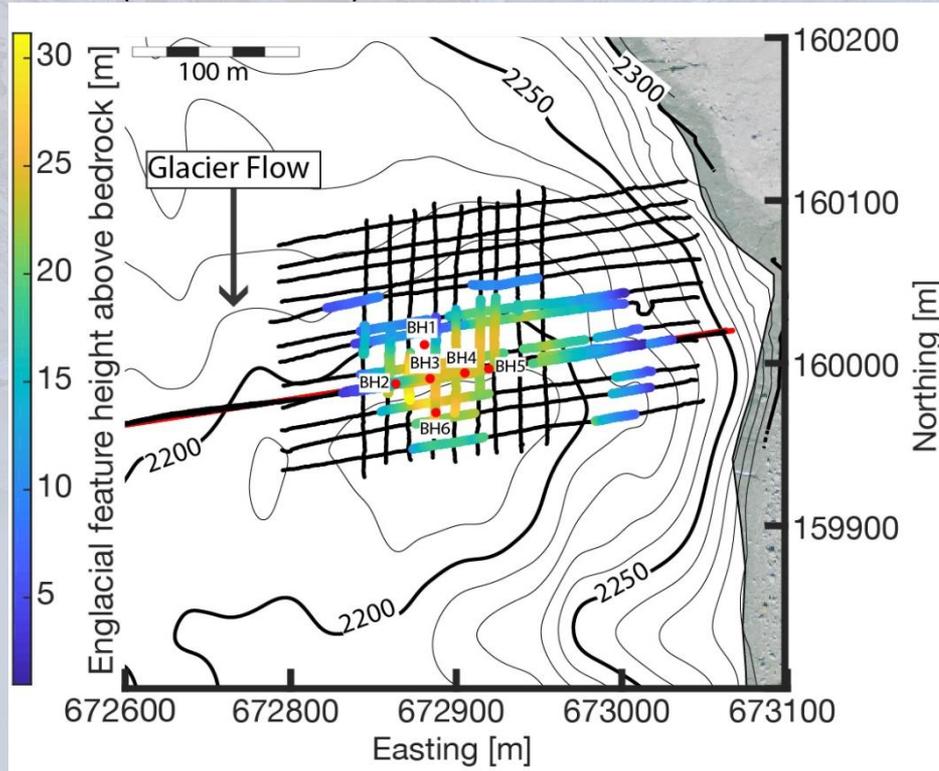
$$A_0 = \frac{A_r(0)^2 d_r(0)}{2 \cdot A_m(0)}$$



- Reflectivity from seismic data follows ice-water reflectivity from Zoeppritz

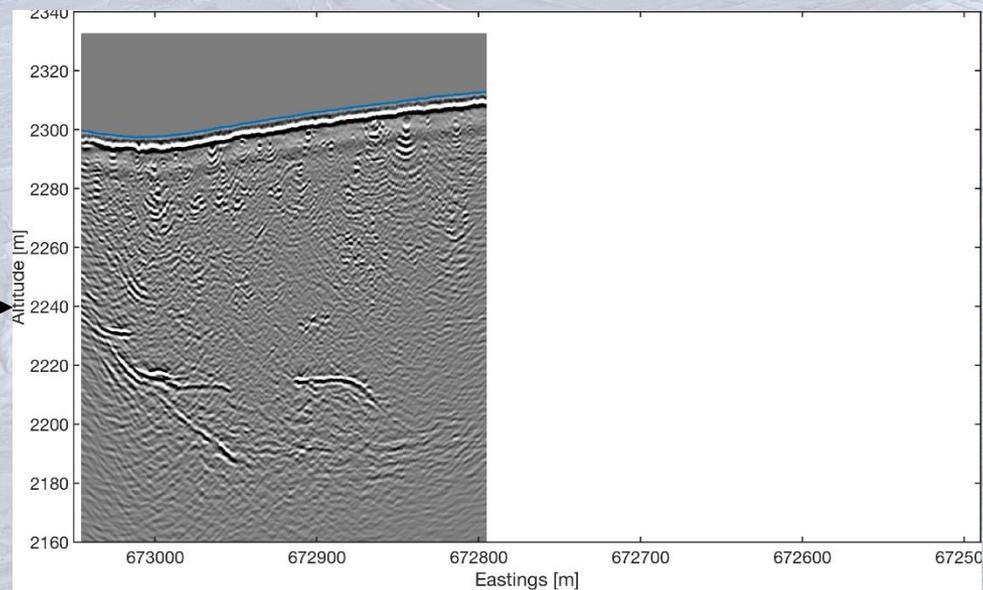
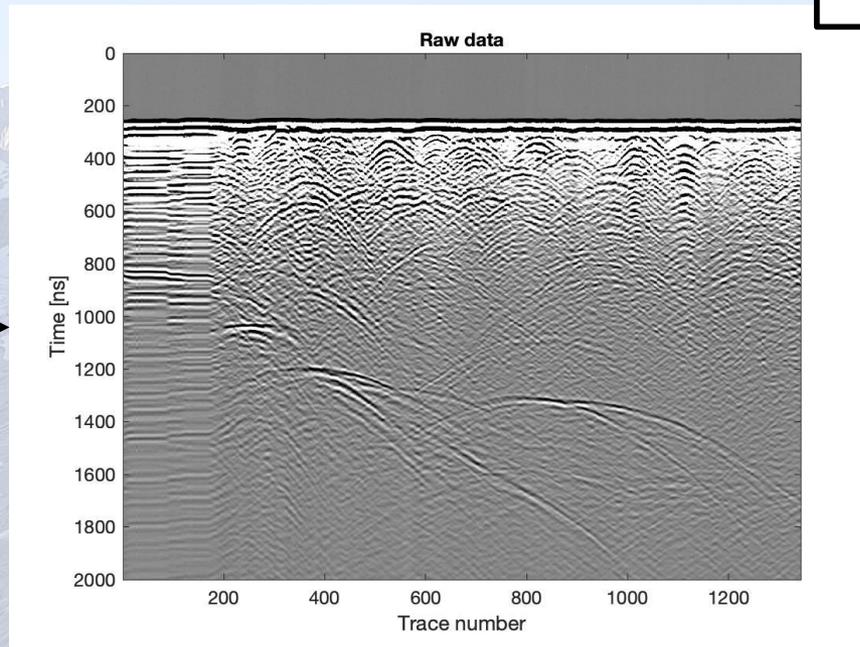
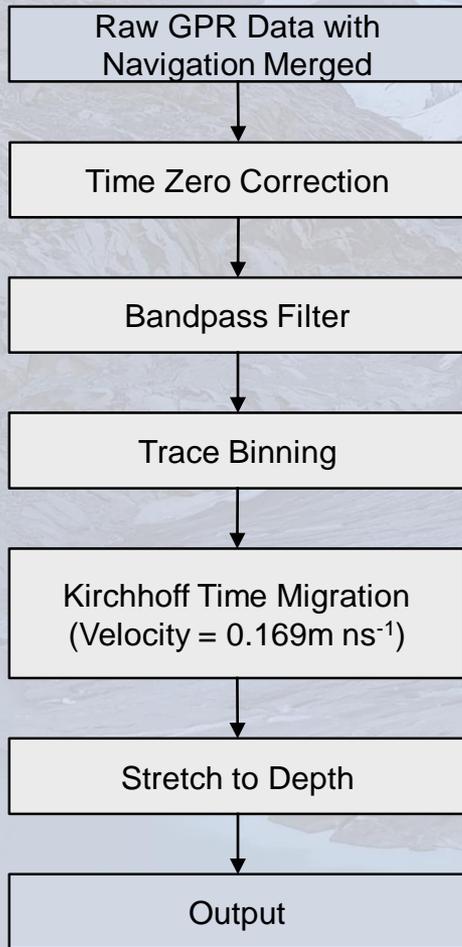
3. Results: GPR Imaging

- We acquired ~7 km of GPR profiles around the englacial feature in the summer of 2018.
- The data was processed using in-house MATLAB-based suite called GPRglaz. [Click for processing details](#)
- Englacial feature remained active after a winter season and was visible over 14,000 m² (map shows height above bedrock of englacial feature).
- Highly resolved and strong bedrock reflection (yellow arrows) and englacial reflection (blue arrows).





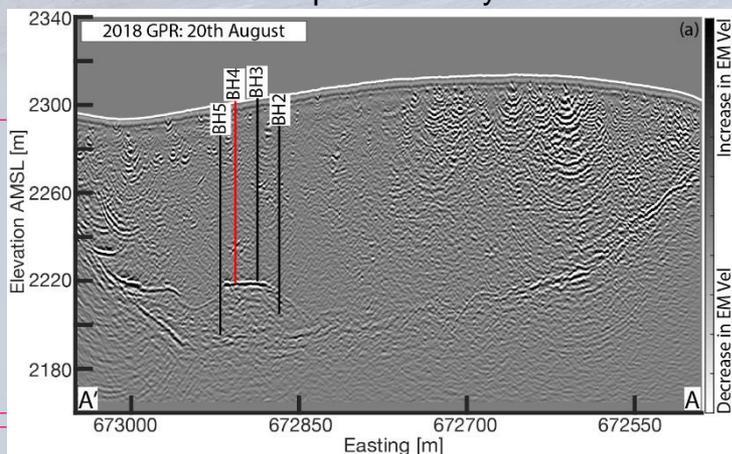
3. Results: GPR Processing





3. Results: Borehole Observations

- We drilled 6 boreholes in August 2018 to confirm and provide direct observations of the englacial conduit network:
 1. The englacial water was murky and turbiditic, with a visibility approximately 20-50 cm.
 2. At the borehole base, the englacial feature showed large quantities of sediment.
 3. The camera shook violently, when positioned within the englacial feature and sediment was being transported at the base. Both observations indicate an englacial flow within the feature.
 4. The side camera did not provide any information on the size of the feature due to the poor visibility.



3. Results: Borehole Water Pressure

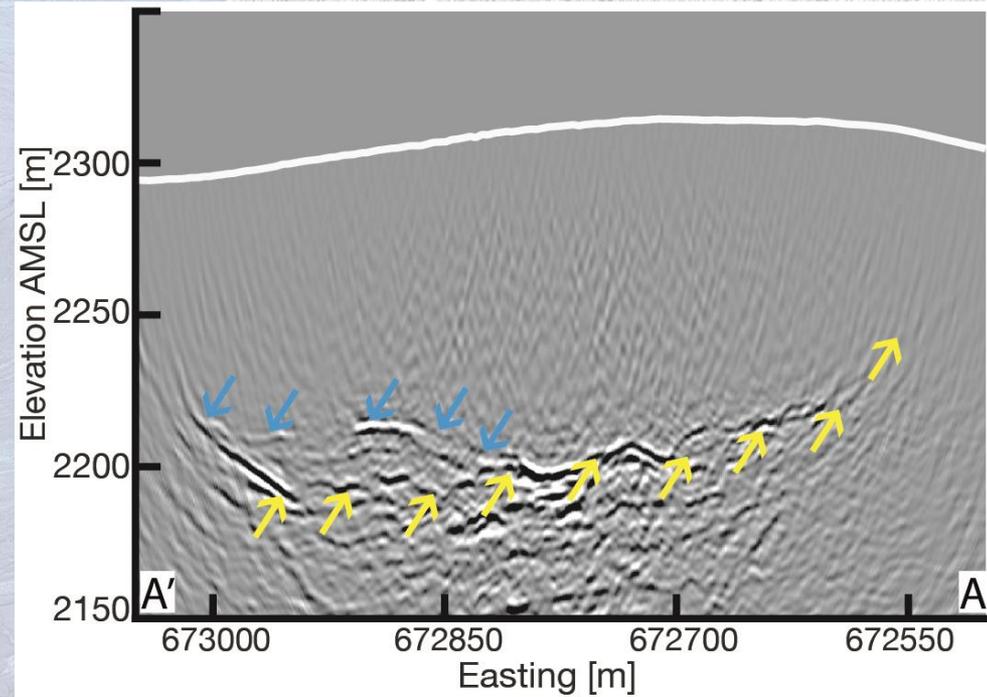
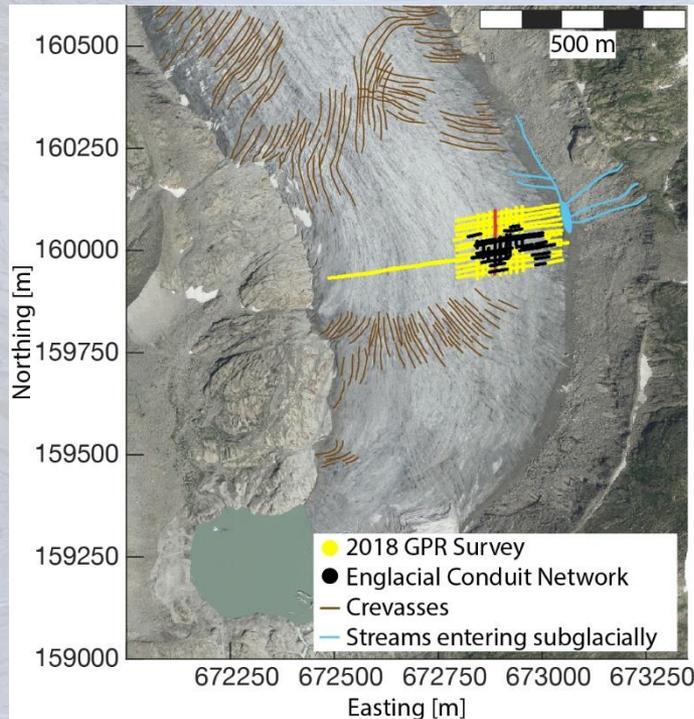
- For the majority of 2018 borehole campaign the englacial water pressure was relatively constant (1-2 m above the englacial conduit with small fluctuations) indicating pressure around atmospheric pressure.



- On numerous occasions, we observed geyser-like events where englacial water was being blown from the top of the borehole for several minutes.
- These sudden high englacial water pressure events could be the likely cause of the englacial conduit formation.

4. Interpretation (Slide 1/2)

- The englacial conduit network on the Rhone Glacier is not located near surface crevasses or moulins and therefore the source is not from these features.



- We observed surface streams and streams located on the eastern moraine merging together before flowing subglacially. From the seismic data it is possible to interpret the subglacial water paths along the glacier's flank and these subglacial channels eventually connect with the sub-horizontal englacial conduit network (blue arrows).
- Therefore, these surface streams and streams on the eastern moraine are likely the water source for the englacial conduit network.



4. Conclusion (Slide 2/2)

- We have been able to delineate an englacial conduit network covering 14,000 m².
- By acquiring two active seismic datasets that are separated by 5 years we have also been able to identify that the englacial conduit network has developed significantly during this period.
- Continuous englacial reflections on the GPR data acquired both parallel and perpendicular to the ice flow allowed the shape of the conduit system to be identified. The conduit shape on the Rhone Glacier does not conform to the theoretical cylindrical shape described by Röthlisberger (1972) and Nye and Frank (1973).
- By using combined geophysical interpretation, we have been able to identify the source as surface and morainal streams flowing along the flank of the glacier and entering the englacial network.
- Water pressure was close to atmospheric pressure within the conduits.
- Borehole camera images provided an insight into englacial conduit conditions. We conclude that the englacial flow within the conduit network was transporting sediment along its base.

5. References

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